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SHOCKTUBE FOR BLAST/FIRE INTERACTION STUDIES.(U)

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SHOCKTUBE FOR BLAST/FIRE INTERACTION STUDIES

Stanley B. Martin
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333 Ravenswood Avenue
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11 August 1980

Final Report for Period 1 April 1978—1 January 1979

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Overpressure
Physics of Extinction

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A 30-inch-diameter, air-driven shocktube was designed, constructed, and tested for studying the fluid physics of the interactions of blast waves with burning objects. The facility was designed to simulate ideal pressure-time waveforms of kiloton-to-megaton nuclear explosions in air with independently variable peak overpressures (to at least 25 psi) and positive-phase durations (from less than 100 ms to more than 3 seconds). The need for an excessively long tube to prevent premature rarefaction was avoided by using a system of

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20. ABSTRACT (Continued)

orifices and a receiver tank at the exhaust end of the shocktube. Orifice sizes are chosen to balance in- and out-flows while the test section is pressurized.

This facility is now in routine operation at USAG Camp Parks, California. Its design concepts could be readily scaled up to provide for testing of larger objects such as weapon systems. Appreciably higher peak overpressures could be obtained if needed in other applications. Because of its short turnaround time, this airblast simulator is an attractive alternative to other methods, providing both low cost and convenience of operation and offering a diversity of test parameters not otherwise available.

B

PREFACE

This work was authorized under Contract DNA001-78-C-0230, Program Element D62704H, Project V99QAXN, Task Area, LL22, Work Unit 56.

As a preliminary effort to an experimental study of the interactions of airblast with fires resulting from nuclear exposions, we completed a special simulation facility, whose initial development was supported by funds from the Defense Civil Preparedness Agency, and demonstrated the feasibility of the design concept. Further support of this program by DNA has not, to date, been forthcoming.

Credit for the concept is due Thomas C. Goodale of SRI's Poulter Laboratory. Among those who contributed to successful translation of the concept to an operating facility, Frank I. Laughridge, John R. Nichols, Robert G. McKee, Jr., and Walter Johnson are particularly noteworthy. Much of the construction work was accomplished under subcontract to Steam Specialties Company of San Francisco.

The author is indebted to Colonel John C. Corral, Commanding Officer of USAG Camp Parks, for his patience during the protracted period of construction.

A

Conversion factors for U.S. customary to metric (SI) units of measurement.

To Convert From	To	Multiply By
angstrom	meters (m)	1.000 000 X E -10
atmosphere (normal)	kilo pascal (kPa)	1.013 25 X E +2
bar	kilo pascal (kPa)	1.000 000 X E +2
barn	meter^2 (m^2)	1.000 000 X E -28
British thermal unit (thermochemical)	joule (J)	1.054 350 X E +3
cal (thermochemical)/cm^2§	mega joule/m^2 (MJ/m^2)	4.184 000 X E -2
calorie (thermochemical)§	joule (J)	4.184 000
calorie (thermochemical)/g§	joule per kilogram (J/kg)*	4.184 000 X E +3
curie§	giga becquerel (GBq)†	3.700 000 X E +1
degree Celsius‡	degree kelvin (K)	$t_K = t°_C + 273.15$
degree (angle)	radian (rad)	1.745 329 X E -2
degree Fahrenheit	degree kelvin (K)	$t_K = (t°_F + 459.67)/1.8$
electron volt§	joule (J)	1.602 19 X E -19
erg§	joule (J)	1.000 000 X E -7
erg/second	watt (W)	1.000 000 X E -7
foot	meter (m)	3.048 000 X E -1
foot-pound-force	joule (J)	1.355 818
gallon (U.S. liquid)	meter^3 (m^3)	3.785 412 X E -3
inch	meter (m)	2.540 000 X E -2
jerk	joule (J)	1.000 000 X E +9
joule/kilogram (J/kg) (radiation dose absorbed)§	gray (Gy)*	1.000 000
kilotons§	terajoules	4.183
kip (1000 lbf)	newton (N)	4.448 222 X E +3
kip/inch^2 (ksi)	kilo pascal (kPa)	6.894 757 X E +3
ktap	newton-second/m^2 (N-s/m^2)	1.000 000 X E +2
micron	meter (m)	1.000 000 X E -6
mil	meter (m)	2.540 000 X E -5
mile (international)	meter (m)	1.609 344 X E +3
ounce	kilogram (kg)	2.834 952 X E -2
pound-force (lbf avoirdupois)	newton (N)	4.448 222
pound-force inch	newton-meter (N·m)	1.129 848 X E -1
pound-force/inch	newton/meter (N/m)	1.751 268 X E +2
pound-force/foot^2	kilo pascal (kPa)	4.788 026 X E -2
pound-force/inch^2 (psi)	kilo pascal (kPa)	6.894 757
pound-mass (lbm avoirdupois)	kilogram (kg)	4.535 924 X E -1
pound-mass-foot^2 (moment of inertia)	kilogram-meter^2 (kg·m^2)	4.214 011 X E -2
pound-mass/foot^3	kilogram/meter^3 (kg/m^3)	1.601 846 X E +1
rad (radiation dose absorbed)§	gray (Gy)*	1.000 000 X E -2
roentgen§	coulomb/kilogram (C/kg)	2.579 760 X E -4
shake	second (s)	1.000 000 X E -8
slug	kilogram (kg)	1.459 390 X E +1
torr (mm Hg, 0° C)	kilo pascal (kPa)	1.333 22 X E -1

*The gray (Gy) is the accepted SI unit equivalent to the energy imparted by ionizing radiation to a mass of energy corresponding to one joule/kilogram.
†The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
‡Temperature may be reported in degree Celsius as well as degree kelvin.
§These units should not be converted in DNA technical reports; however, a parenthetical conversion is permitted at the author's discretion.

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LIST OF ILLUSTRATIONS

SECTION 1

INTRODUCTION

Fire is an important cause of the damage resulting from explosions of nuclear weapons,[1] in tactical[2] as well as strategic[3] employment. Although fire is not usually considered a prime factor in targeting because its destructiveness is notoriously so difficult to predict, it cannot be ignored as a collateral effect.[4] In fact, its consequences may outweigh all other effects combined.

Among the factors limiting fire damage (and the major sources of uncertainty in fire-damage prediction), airblast interactions are unique, both in potential importance and in the extent of our ignorance about them. The importance of these interactive effects of blast and fire has been recognized for a considerable time, but only a limited research effort has been directed toward understanding and quantitatively evaluating them. These effects include the dynamic influences (enhancement as well as extinguishment) of the passage of the air shock over ignited materials and the perturbations in fire growth and spread caused by the residual disarray produced in target elements by blast effects. This research has provided some insight, but the remaining contradictions can be resolved only through additional experimental study, complemented by the development of a rational methodology for combined-effects damage assessment.

Of the several critical uncertainties, perhaps the one that overshadows all others is the extinction (or suppression) of fire by air blast since it raises such questions as: How many (if any) fires survive the blast, in what conditions, and in what locations? In short, we cannot predict the combinations of conditions that either suppress primary fires--reducing them for a time to a smoldering state--or extinguish them outright. Indeed, we have not been able to decide, to date, which of the many variables are the important ones. The facility described in this report was developed specifically to overcome this technical deficiency.

SECTION 2

OBJECTIVES

The overall objectives of the research were to

(1) Determine the physical mechanisms of extinction of fire by blast waves and ascertain scaling relationships.

(2) Develop computational models for fuel elements in free-field disposition and urban enclosures.

(3) Test the validity of model predictions in a future field test (e.g., Misty Castle).

The work reported here represents an initial effort to partially satisfy Objective 1 by completing the development of the necessary experimental facility. Ideally, this research program should progress through iterative cycles. The first iteration might be scheduled to conclude with field-test validation of hypotheses derived from a limited experimental effort, at a suitable HE shot in the Misty Castle series. Considering the complexity of the blast-fire interaction problem, it is unreasonable to expect that the whole problem can be resolved in a single iteration of two year's duration. Nevertheless, we are confident that we will have significantly advanced our understanding of the interactions when that initial iteration concludes with the experiements planned for the upcoming MILL RACE event of the Misty Castle series.

SECTION 3

PROGRAM STATUS

The SRI-developed shocktube facility was completed and tested during this contract period. It is now fully operational and is being used to investigate airblast extinction of fires under contract to the Federal Emergency Management Agency (FEMA). In this way, a partial demonstration of its utility and versatility has been afforded; however, its full potential cannot be realized until further investment is made in diagnostic instrumentation and in refining the system of orifices, diaphrams, the receiver tank, and other accessories that provide the capability for unusually long positive-phase durations and the independent control of overpressure, duration, and decay of particle velocity behind the shock.

This section describes the design and operation of the shocktube facility and the limited tests conducted to improve its operation. Later use of the facility in studies of fire extinction funded by DCPA/FEMA is also described.

FUNCTION OF THE SHOCKTUBE FACILITY

In all previous experiments, the blast-wave simulations have been inadequate to permit resolution of the many variables involved in most practical situations. The fundamental weakness in experiments conducted to date has been their lack of independent variability of peak overpressure, positive-phase duration, and flow behind the shock front. Such variability would allow systematic study of fire extinguishing mechanisms and the dependence of extinction on pertinent aerodynamic conditions that can vary so widely, especially in an urban target.

The SRI-developed blast/fire facility was specifically designed for used in studying blast/fire interactions by allowing the phenomena to be observed directly, providing repeatability of test conditions and convenience of operation, and making systematic investigation possible through independent variability of air blast characteristics over the practical range of values in which fire effects are significant.

DESCRIPTION OF THE SHOCKTUBE FACILITY

The facility is illustrated in Figure 1. The central feature is the 30-inch-diameter, air-driven shocktube specifically designed for experiments in blast-fire interactions. This shocktube produces blast waves that simulate the characteristics of kiloton-to-megaton nuclear explosions in air. Peak overpressures and positive-phase durations are preselected and controlled by the operator. Overpressures are determined by choice of initial pressure in the plenum that drives the shocktube. The duration is controlled by a mechanism for relief of plenum pressure by diverting a portion of the airflow from the shocktube.

The facility is designed to provide peak overpressures up to at least 25 psi and positive-phase durations from about 0.10 to more than 3.5 seconds. A system of orifices at both ends of the shocktube, combined with a receiver tank at the exhaust end, match the outflow of the receiver tank (when it is fully pressurized) to the outflow of the plenum to prevent the premature rarefaction of the test section. The facility includes a telescoping test-section closure that allows fires to become established, while burning in the open breach, before being enclosed. The breach is then closed, just as the shock is initiated, with minimal delay to prevent depriving the fire of oxygen. For safe operation, this closure must occur automatically upon command from a remote location.

The shock is initiated by explosively shearing the pressure-stressed (typically dead-soft aluminum) diaphragm with a Detasheet line charge arranged as an asterform with capitals. This cuts the diaphragm cleanly, nearly instantaneously, and allows the diaphragm to fold back smoothly against the walls of the tube for minimal interference with the expanding air flow. A similar technique is planned for use on the diaphragms of the multiapertured plenum relief (which is included as a separate control of the positive-phase duration) but so far we have not had occasion to use this feature.

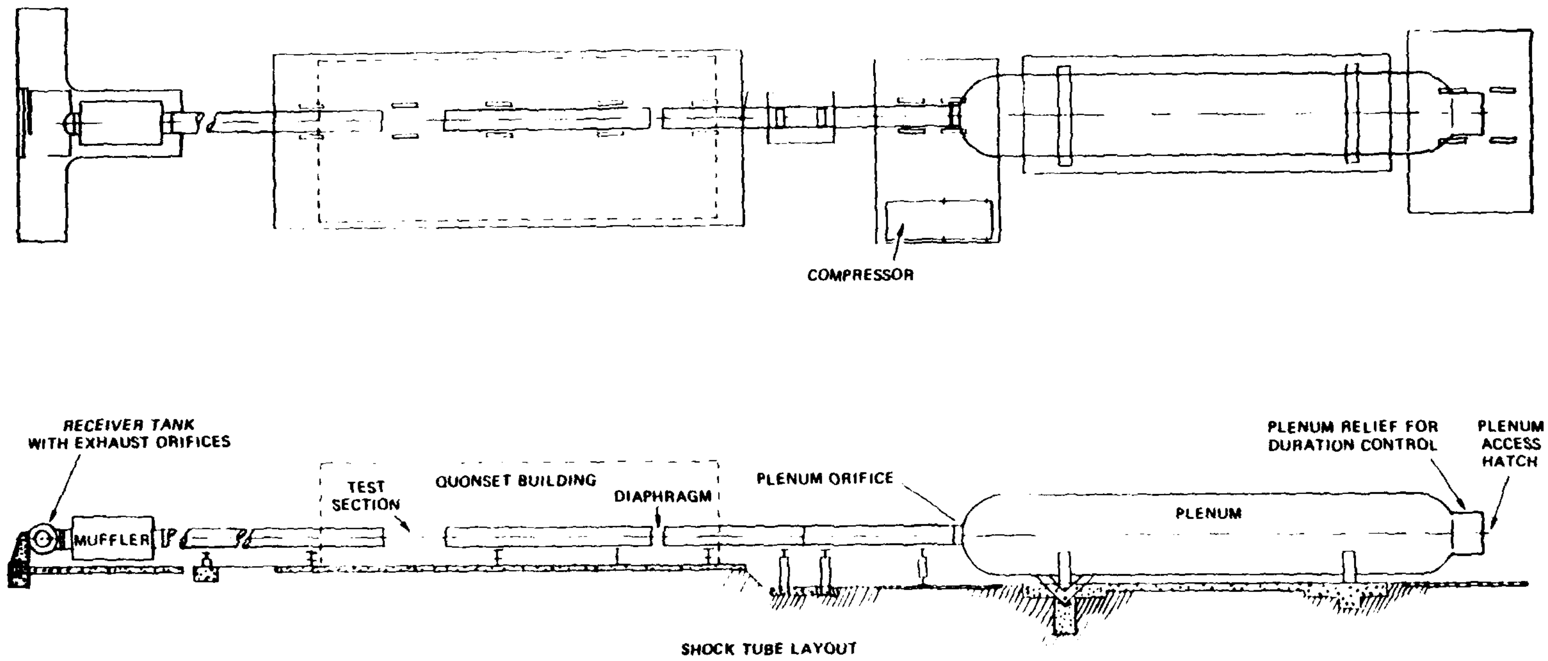

FIGURE I   BLAST/FIRE SHOCKTUBE FACILITY

PERFORMANCE WITHOUT FIRES, DIAGNOSTIC REQUIREMENTS

The first shot was fired on 19 December 1978. A plenum pressure of 17 psig produced a remarkably clean, nominally $5\frac{1}{2}$ psi, peak-overpressure shock wave of $3\frac{1}{2}$ s positive-phase duration (see Figure 2). The long positive phase with only minor perturbation due to premature rarefaction is a singular achievement, and the generally successful results are remarkable for a first try. The shock-dissipation "muffler" at the end of the tube worked as it was designed to, degrading the emerging shock so completely to potential flow as it entered the receiver tank that nearby observers heard more of a "whoosh" than a "bang."

The Detasheet technique for rupturing the pressure restraining diaphragm also worked exactly as designed, instantly parting the aluminum into six petals that folded flat against the tube walls with minimal retardation of the flow of air driving the shock and no introduction of extraneous materials or diaphragm fragments into the test section. There is no doubt that this technique will work equally well on the multiapertured plenum relief device, and thereby allow the pressure pulse duration to be varied in small steps down to less than one-tenth of the value resulting from this test, in which all the compressed air in the plenum exhausted through the shocktube.

Several nonideal characteristics were noted in the pressure-time pulse of Shot 1, shown in Figure 2. A 20-ms spike of roughly 1 psi amplitude appears on the shock front and is followed 50 to 60 ms later by a similar spike of somewhat reduced overpressure. It is reasonable to suppose that the first spike results from the impulse of the detonating Detasheet asterform used to cut the diaphragm.

The second spike could then be explained as a reflection from the upstream orifice of the counterpart shock created by the same impulse--transmitted through the aluminum of the diaphragm--since the path up and back is just over 60 ft (i.e., if we take 1120 ft/s as the speed of sound in air, the approximate shock transit time would be $60/1120 = 0.53$ s). Since the orifice diameter was about half the tube diameter, three-quarters of a plane shock wave could be returned by reflection.

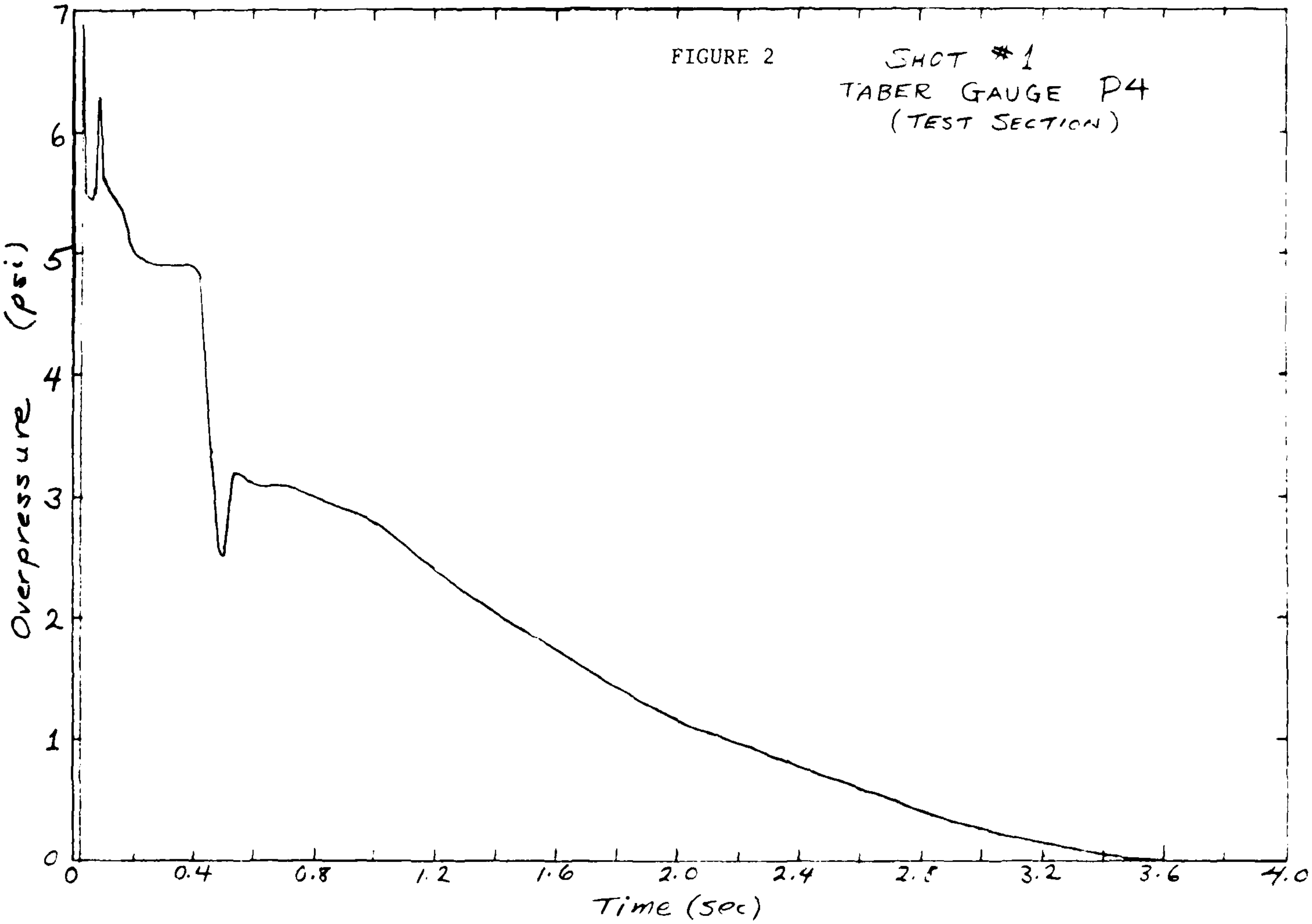
SHOT #1
TABER GAUGE P4
(TEST SECTION)
Overpressure (psi)
Time (sec)
0
1
2
3
4
5
6
7
0.4
0.8
1.2
1.6
2.0
2.4
3.2
3.6
4.0

FIGURE 2

These spikes would be proportionately more objectionable at lower peak overpressures; therefore, we have considered other techniques of diaphragm rupture that do not employ explosives. One such technique uses electrically heated wires to cut nonmetallic diaphragms, e.g., Mylar sheet.

The relatively flat-topped portion of the pressure pulse (up to about 400 ms) is not fully understood. Further attention should be paid to this nonideal behavior.

An abrupt drop in pressure was observed after 400 ms at the test section and after 300 ms at a pressure monitoring station about half way downstream the tube. This pressure drop is presumably* caused by the returning rarefaction that was inadequately suppressed by the flow-control orifices and/or receiver tank volume originally chosen. Some mismatch was entirely expected on the first shot because the state of the art does not permit exact calculation of orifice discharge coefficients. Nevertheless, the pressure decay remained positive throughout the perturbation, and the normal-decay waveform was restored after 1 s.

Our second shot, fired on 20 December 1978, was an attempt to correct the perturbation due to premature rarefaction. Premature rarefaction can result from any of several design mismatches. Either an oversized set of relief orifices in the receiver tank or an undersized orifice between plenum and tube would delay the filling of the receiver tank and prolong the rarefaction process. That is, the orifices must be matched relative to each other, but in addition the absolute values must be large enough to permit the flow behind the shock to decay as it would in free air. Moreover, the volume of the receiver (including the volume of the muffler chamber) must be matched to the quantity of air supplied to it. The simple pressure-time information available from the first shot was not sufficient to ascertain the modification required; therefore, we arbitrarily chose to reduce the diameters of the downstream orifices for the second shot.

*The times of appearance are entirely consistent with the propagation rates and distances.

The second shot was intended to be an exact duplicate of the first except for the change in downstream orifice size. However, because we lacked control of plenum air temperature, it was necessary to compensate for the lower temperatures on the second shot (resulting from less solar heating of the tank) by increasing the pressure. The pressure at the time of firing was 18.4 psig.

Figure 3 compares the record for the second shot with that from the first, illustrating the close similarity of the two for the first 54 ms. Unfortunately, spot welds holding the cover of the muffler section let go about the time the pressure in the muffler chamber reached its peak, thereby shortening the positive phase. The effect of this shortening was apparently not felt at the test-section pressure gage until after the rarefaction wave reached it, so the record provides evidence that our remedy was unsuccessful. We now suspect that a better choice would have been to enlarge the upstream orifice.

Nevertheless, this second test was very useful, and it nicely illustrates the pitfalls in trying to remedy design mismatches without sufficient and appropriate diagnostic measurements. It also gives unmistakable evidence of the validity of the design concept. The sudden loss of pressure from the muffler resulted in an abrupt increase in the rate of decay of positive pressure. Note that sudden decompression of the muffler chamber does not produce immediate blowdown of the receiver tank, since the two are connected through a series of small holes. This accounts for the somewhat gradual loss in pressure instead of abrupt termination of the positive phase. The test also showed that, with proper diagnostics, we could proceed with confidence to determine what is needed to eliminate the perturbing effects of premature rarefaction.

STUDIES OF FIRE EXTINCTION*

All use of the facility since December 1978 has been restricted to studies of fire extinction. Before this feature of the facility could

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*This summary of effort funded by DCPA/FEMA is extracted from Reference 5.

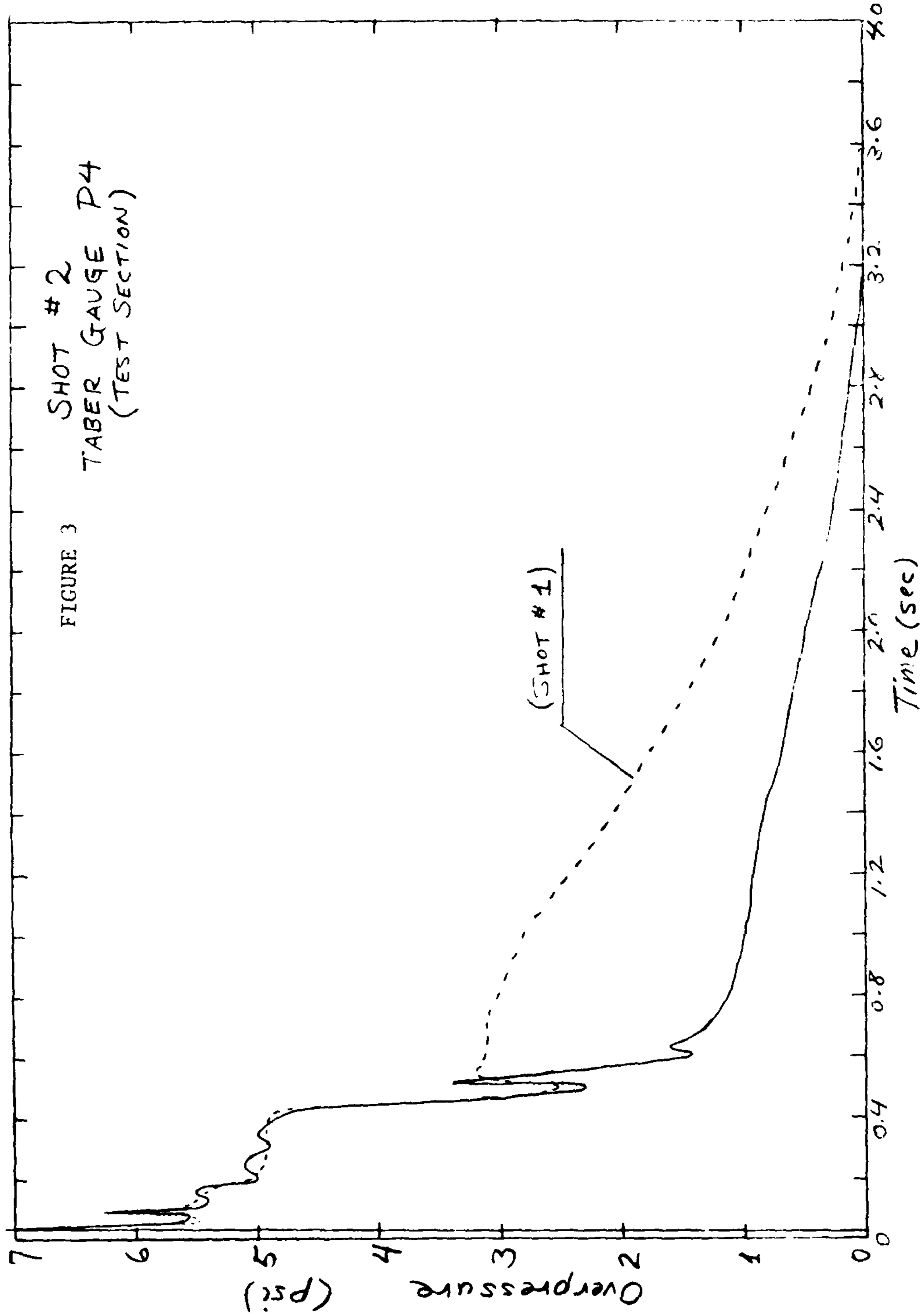
SHOT #2
TABER GAUGE P4
(TEST SECTION)
(SHOT #1)
Overpressure (psi)
0
1
2
3
4
5
6
7
Time (sec)
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0

FIGURE 3

be exploited, it was necessary to modify the test section of the shocktube to provide a fuel supply, fuel bed support, and a means for fast, semiautomatic closure of the test-section breach. Test target design requirements were complicated by the necessity of supporting the ensemble without interfering with either the operation of the telescoping breach closure or with the shockwave as it approaches the target.

TEST SECTION MODIFICATIONS

The initial experiments were visualized to be idealizations of the kerosene/gravel fuel beds used at Mixed Company.[6] To minimize perturbations in the air shock and subsequent flow, a thin, flat plate having sharp leading and trailing edges was chosen as the basic form of the fuel bed support. This platform, illustrated in Figure 4, is rigidly supported in a near midstream position by a sharp-edge cantilever attached to the stationary shocktube section just forward of the test section opening. The platform accepts 10-inch-wide fuel beds of variable lengths up to 37 inches along the direction of shock propagation. The fuel is set into a recess on the top surface and is ordinarily flush with the top surface. The telescoping section is closed on remote command, initiating an automatic sequence to start the cameras. After a 1.6 s delay, to allow the film to accelerate to full speed, the line charge asterform on the diaphragm is fired to initiate the shock. A borosilicate glass window in the sliding section allows the fuel bed and flames over it to be observed and recorded on film.

Measurements are limited to temperature-time and overpressure-time records. The principal form of target response information, besides the postshot observation of whether extinguishment has occurred, is provided by high-speed color photography (approximately 2000 frames-per-second framing rate) of the flames during shock diffraction and the period of subsequent hydrodynamic motion.

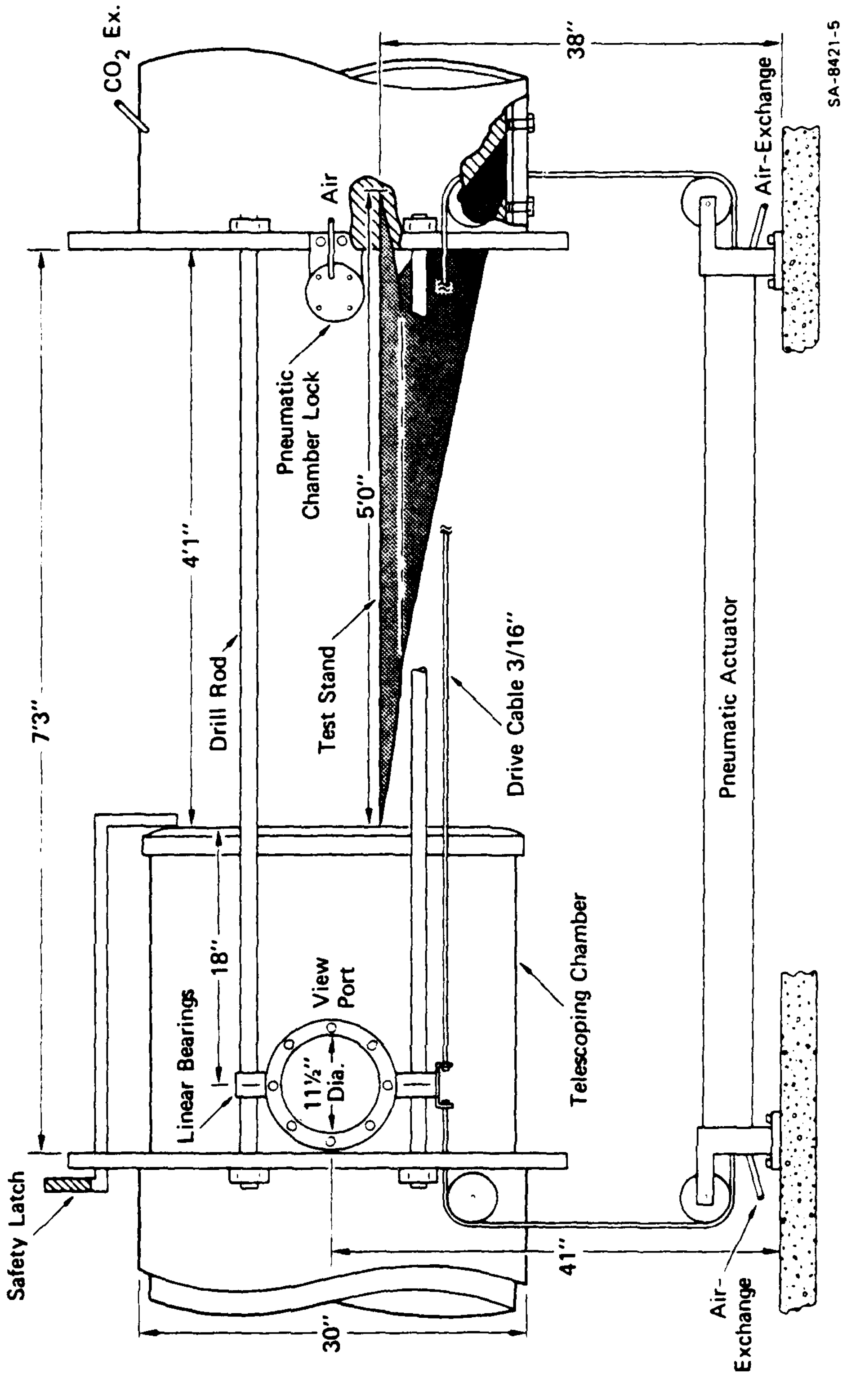

FIGURE 4 SHOCKTUBE TEST SECTION

FLAME DISPLACEMENT OVER FUEL-SOAKED WICKS

The initial experiments modeled the inconclusive experiments run in the field in 1972 at Operation Mixed Company.[6] n-Hexane was chosen as a Class B fuel substitute for the kerosene used at Mixed Company. This change was felt to be desirable mainly because the use of a single substance of well-defined properties avoids possible ambiguities of less well-defined mixtures whose properties can change with time, but also because hexane is somewhat cleaner burning (less sooty) than kerosene.

The first set of Class B fuel tests was run with the longest available positive-phase durations. Comparison of the pressure pulses from shots 4 and 5 (Figures 5 and 6) suggests that we were able to make progress toward eliminating the perturbing rarefaction without the help of diagnostic instrumentation; however, that may not be so, because the effects of the flames may be obscurring pressure transients in these tests.

Consistent extinction of flames occurred at all overpressures down to about 1 psi (where the pressure spike from the line-charge explosive used to cut the diaphragm appreciably perturbs the air-driven pressure pulse). Therefore, we decided to drastically shorten the pulse duration, but rather than using the alternative venting feature, we chose to blank off the tank at the orifice flange and use only the 33.5-foot section of tube between the diaphragm and the tank as the pressure plenum. For the remainder of experimental work reported in Reference 5, we continued to operate in this short-duration mode. Example pressure pulses are shown in Figures 7 and 8.

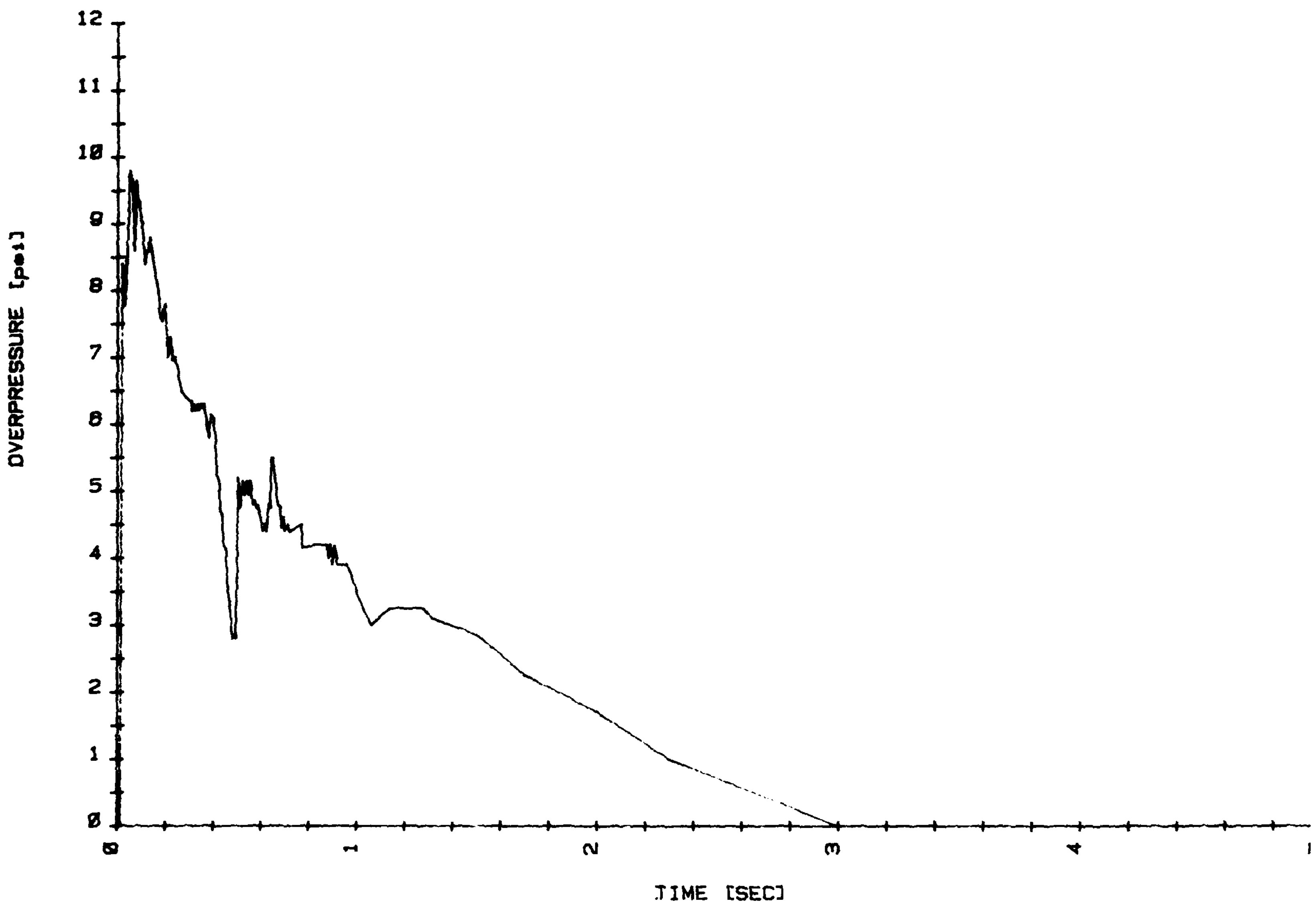

FIGURE 5 PRESSURE-TIME PULSE, SHOT 4

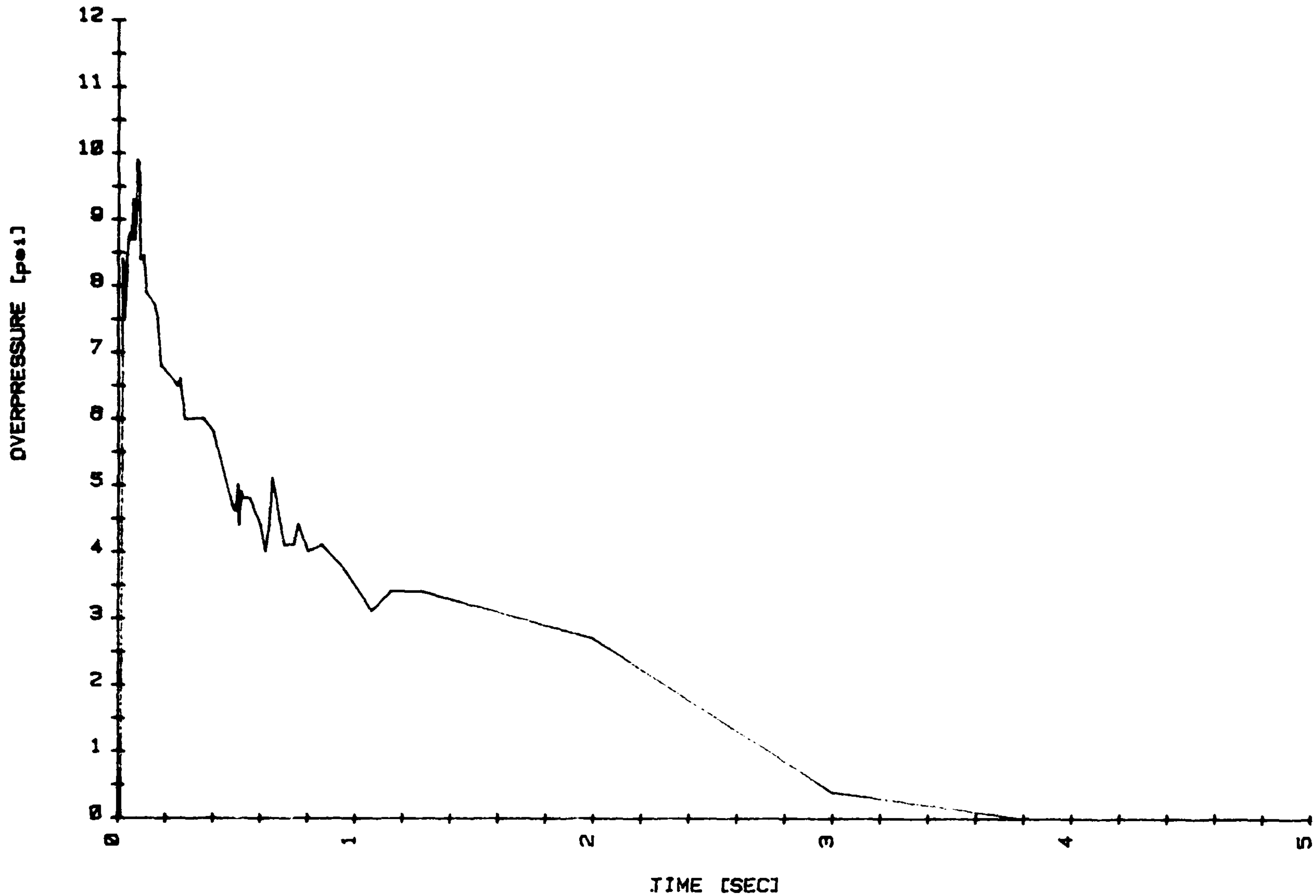

FIGURE 6 PRESSURE-TIME PULSE, SHOT 5

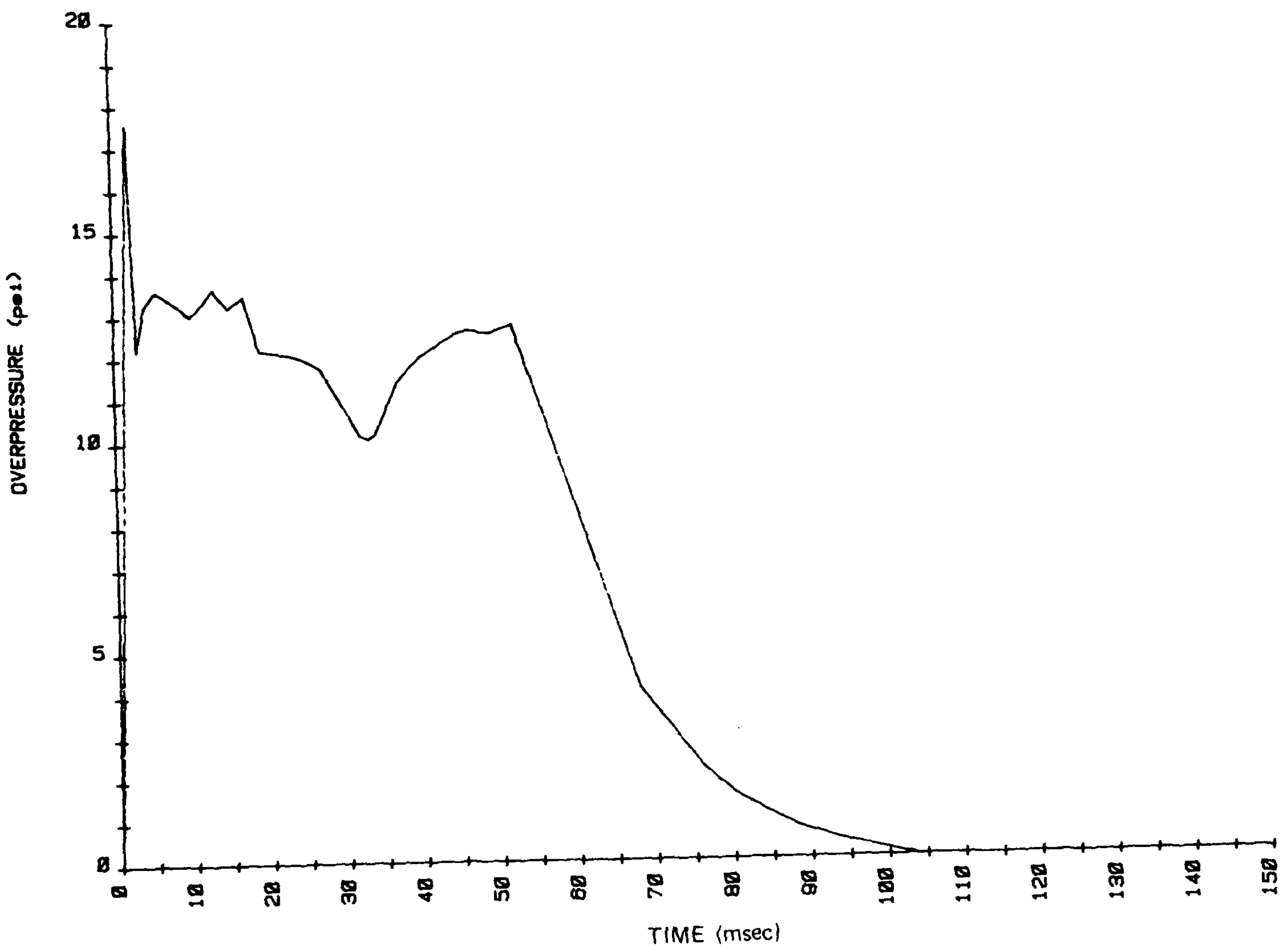

FIGURE 7 PRESSURE-TIME PULSE IN SHORT DURATION MODE, SHOT 70

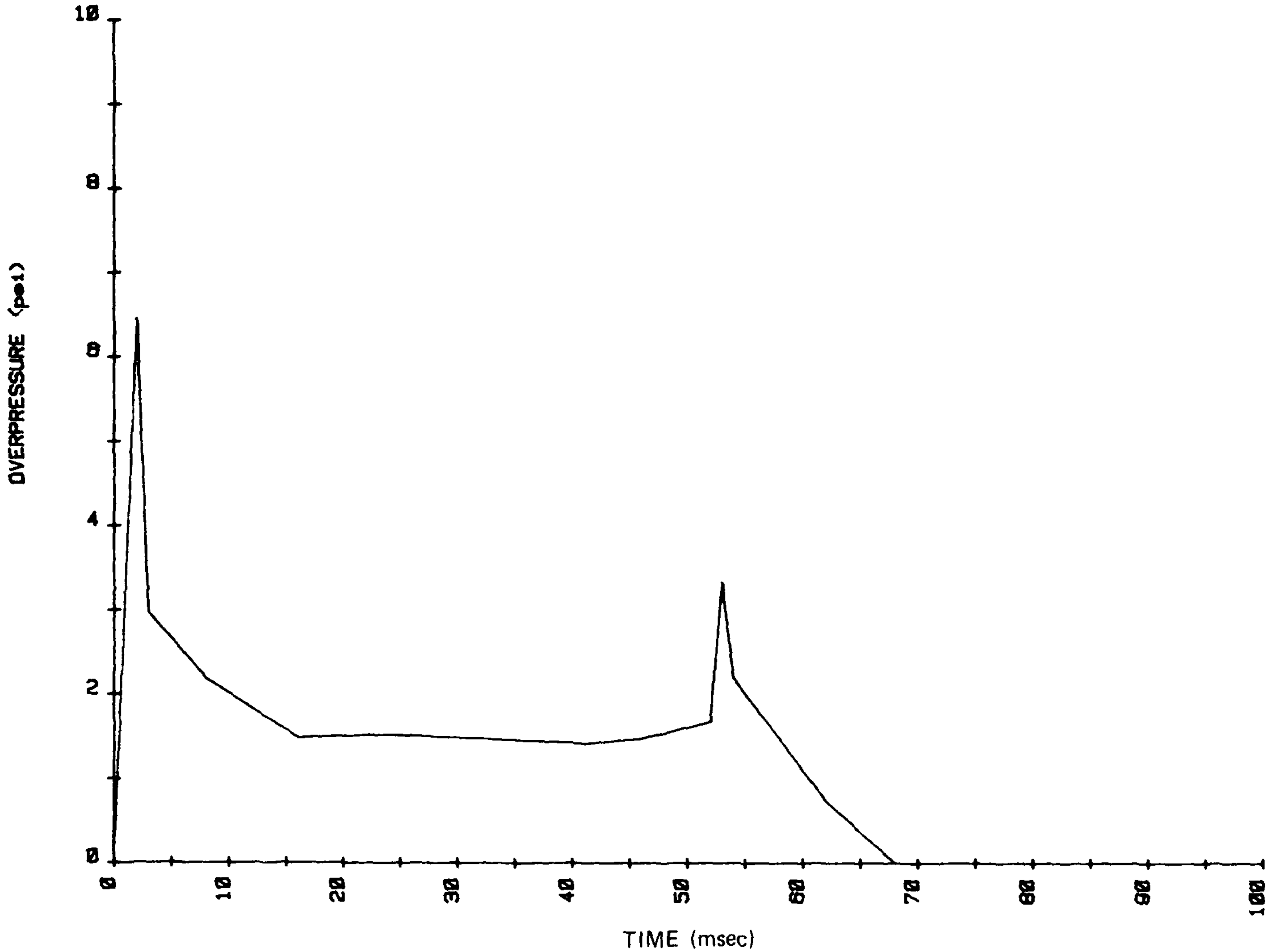

FIGURE 8 PRESSURE-TIME PULSE IN SHORT-DURATION MODE, SHOT 42

SECTION 3

RECOMMENDATIONS

We believe that DNA has unique requirements that can be met advantageously through the use of this research facility. Its applicability to problems of fire as a collateral effect of nuclear explosions is self-evident, and we recommend that the facility's unique features be used to further our understanding of the basic physics of interaction of air blast with fires in support of tactical and strategic targeting as well as in support of national preparedness (e.g., FEMA) planning. We also suggest that there are quite probably other uses for this facility that have nothing to do with fire problems, and we urge DNA to consider the facility's unique capabilities with other nuclear weapons effects research applications in mind.

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